CALIOP's V4 Algorithms for Retrieving Optical Properties in Opaque Ice Clouds

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Aims

- Better estimates of particulate lidar ratio, S_P, and uncertainty, ΔS_P,
- Retrieve accurate particulate backscatter, $\beta_P(r)$, & extinction, $\sigma_P(r)$, deeper into layer.
- Reduce uncertainties $\Delta\beta_P(r)$, $\Delta\sigma_P(r)$.

Difficulties Faced

- For high optical depths (τ_P), S_P must be very accurate. (See plots (a) & (b) below.)
- Considerable natural variability exists in S_P,
- Possible large differences between CALIOP's default S_P and true value.

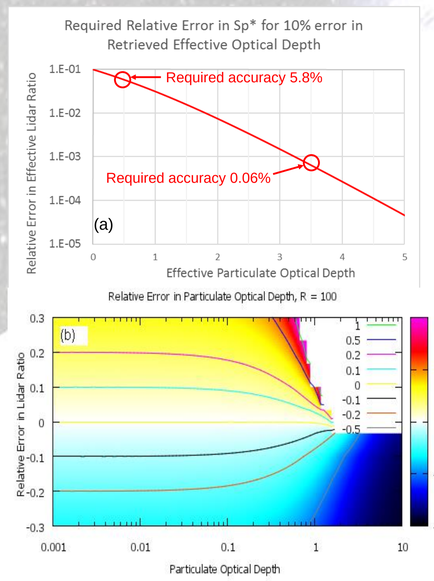

Fig.1(a),(b): Relative errors in retrieved particulate optical depth as a function of relative error in lidar ratio.

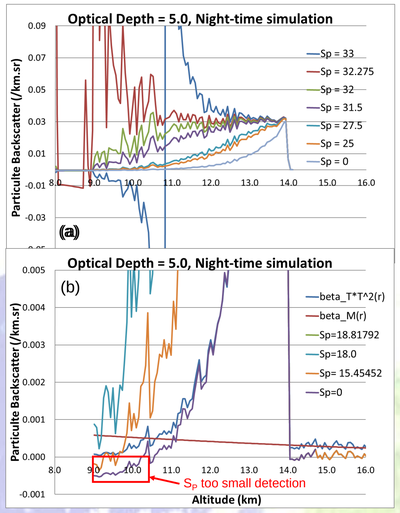

Fig.2(a),(b): Retrievals on simulated data showing sensitivity to S_P. Modeled S_P = 32 sr, Modeled η = 0.6.

Version-3 Algorithm

- V3 algorithm – conflicting requirements:
  - Very fine adjustments of S_P give more accurate retrievals BUT can require too many adjustments causing premature termination,
  - Coarser adjustments guarantee a retrieval but final S_P usually too small causing $\sigma_P(r)$ and $\tau_P(r_{top}, r_{detected\_base})$ to be too small.
- The compromise employed:

1. Least Upper Bound and Greatest Lower Bounds of S_P set to maximum and minimum acceptable values of S_P,
2. Retrieval begun at top of feature with default S_P,
3. At each range step, r, perform test:

IF retrieval diverges high ($\beta_P(r)$ becomes undefined), THEN reduce S_P:

- Increment number of Sp adjustments.
- Set Least Upper Bound for S_P to Minimum of current value and current S_P.
- IF number of S_P adjustments is less than or equal to 5, THEN reduce S_P by 1%,
- ELSE set S_P to Maximum of current Greatest Lower Bound of S_P and a 5% reduction of current S_P.

IF retrieval diverges low (rarely detected) (β_P (r) <0 where β'_T (r)> 0),THEN increase S_P:

- Increment Number of S_P adjustments.
- Set Greatest Lower Bound of S_P to Maximum of Current Value and current S_P,
- IF number of Sp adjustments is less than or equal to 5 THEN increase S_P by 1%,
- ELSE Set S_P to average of current Least Upper Bound and current S_P.

4. dSp unchanged,
5. Restart from top of layer (Return to step 3).

Version-3 Algorithm Consequences

- V3 retrievals often trend low with increasing penetration into layer,
- Optical Depth histograms show artifacts related to 1% and 5% reductions in S_P. (See pale green curve in Fig. 3.)

Reference

Fernald F. G., Herman B. M., and Reagan J. A. (1972) Determination of aerosol height distributions by lidar. *J. Appl. Meteor.*, **11**, 482–489.

Version-4 Algorithm

- Improved performance from
  - New S_P, dS_P, and η (See Garnier poster),
  - Better initial S_P and dS_P,
  - S_P adjustments a function of reciprocal of average retrieved extinction from layer top.

1. Multiple-Scattering Correction Factor, η, now a function of cloud temperature.
2. Further refinement #1:

$$S_{P,init} = 1/(2\eta\gamma_P'(r_t,r_b))$$

where $\gamma_P'(r_t,r_b)$ = Layer integral of attenuated total backscatter.

3. Further refinement # 2:

$S_{P\ init}$ obtained by solving Eq. 15 of Fernald *et al.* (1972) with $T_P^2(r_t,r_b) = 0$ and using $S_{P\ init}$ from step 2. in an iterative solution of this transcendental equation (~ 3 iterations):

$$S_P = \frac{1 - T_P^{2\eta}(r_t,r_b)\,T_M^{2\left(\eta S_P / S_M\right)}(r_t,r_b)}{2\eta\int_{r_t}^{r_b}\left[\beta_T(z)T_P^{2\eta}(r_t,z)T_M^2(r_t,z)\right]T_M^{2\left(\eta S_P/S_M - 1\right)}(r_t,z)\,dz}$$

3. Rescale dS_P to maintain relative uncertainty.
4. Proceed as in V3 algorithm with these modifications:

- For each range, r, calculate $\tau_P(r_t,r)$,$T_P^2(r_t,r)$, & average extinction, $\sigma_{ave} = \tau_P(r_t,r)/(r-r_t)$.
- If retrieval diverging high, increase S_P:
  $S_P = S_P\,(1 - T_P^2(r_t,r) / \sigma_{ave})$,
- If retrieval diverging low, decrease S_P:
  $S_P = S_P\,(1 + T_P^2(r_t,r) / \sigma_{ave})$.

Version-4 Algorithm Improvements

- Extinction retrievals, tested using simulated data, have improved accuracy,
- Optical Depth histograms artifacts no longer appear. (See V4 and V3 comparisons in Fig. 3.)

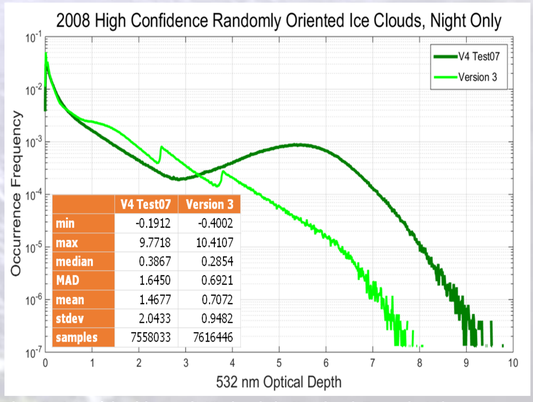

Fig. 3: V4 (dark) andV3 (pale) Optical Depth Histograms.

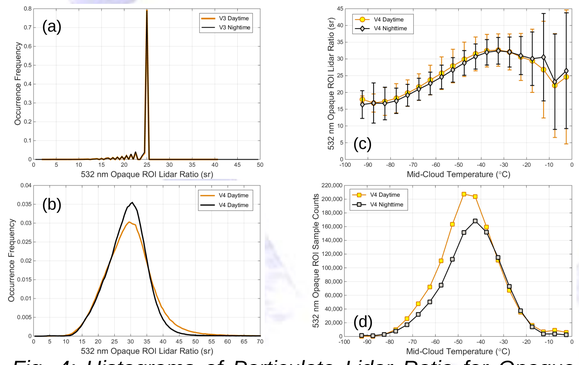

Fig. 4: Histograms of Particulate Lidar Ratio for Opaque ROI clouds for 2008. (a) V3 compared with (b) improvement in V4. Histograms versus Mid-Cloud Temperature (c) V4 Lidar Ratio, (d) V4 Sample Count.

Remaining Caveats (not specific to V4)

- Remember: Reported optical depth is only that retrieved between detected top and base of cloud layer. It is not total column optical depth.
- Retrievals may still be diverging high or low but not sufficiently to trigger correction.
- Misidentification of a layer's being opaque will cause overestimation of S_P, $\sigma_P(r)$ & τ_P.
- Changes of type (and S_P) within a feature column (e.g. ice to water or ROI to HOI, both of which have $S_P < S_{P\_ROI}$) can lead to divergence in region of low S_P causing overall layer S_P to be reduced. Result is that retrieval is underestimated in ROI region and overestimated in HOI / water region. (Examination of depolarization profile may help identify these cases. See Fig. 5. – Also see poster by Avery.)

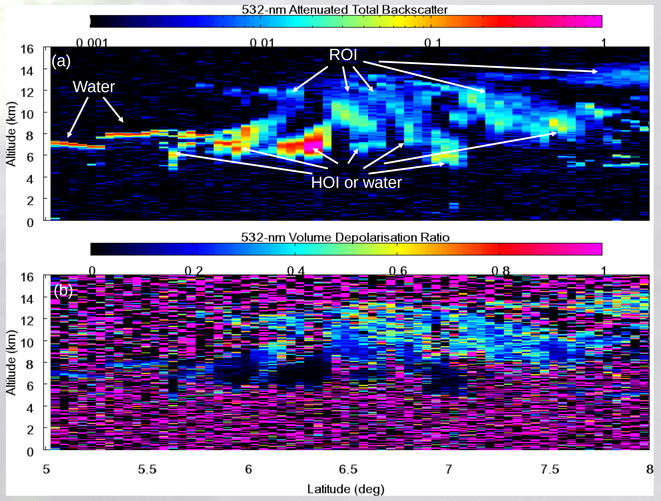

Fig 5: (a) 532-nm attenuated backscatter, (b) depolarization ratio measured in the TC4 Mission showing phase change in lower regions of detected cloud "features". Notes (i) All features are shown as detected at 5-km horizontal resolution, (ii) Lidar signal in all features was totally attenuated below apparent base.